navigation system, craniofacial surgery, bone repositioning, preoperative planning, intra-operative tracking, computed tomography, zygomatic bone

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PREOPERATIVE PLANNING AND INTRAOPERATIVE NAVIGATION IN THE RECONSTRUCTIVE CRANIOFACIAL SURGERY

We present a methodology for navigation-aided surgical treatments in the reconstructive craniofacial surgery. Using the case of zygomatic bone repositioning after gunshot wound trauma the whole preoperative planning process and the intra-operative navigation oriented issues are explicitly described. We have focused our attention on the new navigation oriented aspects and procedures which facilitate and enhance the traditional treatment techniques. Many illustrations let better understand the complex technical dependencies between the main elements of this approach. The presented procedures permit more precise planning and performing of the surgical treatment, reducing intra-operative time and improving the post-operative outcome.

1. INTRODUCTION

In this paper we describe a methodology for the preoperative planning and surgical treatment in the reconstructive craniofacial surgery supported by the optical navigation system. We would like to present this novel approach using as an example the case of zygomatic bone repositioning after gunshot wound trauma. We divide this methodology into two stages. At the first stage the computer aided preoperative planning based on the acquired CT data will be performed. The prepared virtual patient models including the numerically defined treatment goals are used at the second stage of the navigation system aided surgery in the operation theatre. Various aspects of these two main stages will be discussed and explained. The post-operative data acquisition let us to evaluate the results of the performed treatment according to the planning objectives.

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2. PREOPERATIVE TREATMENT PLANNING

Generally, the preoperative surgery planning is needed to formulate the treatment goals and the optimality criteria according to requirements of the applied technology. Because our approach is based on the computerized systems, we need to formulate these criteria in a quantitative way. Mostly, the planning process is performed using the acquired computed tomography datasets. The preparation and processing of the CT data include primarily the segmentation, registration and visualization techniques [2,3]. After segmenting the relevant anatomical structures, the physician can start to explore the virtual anatomical model. The registration methods allow additionally aligning the complementary information from different medical imaging modalities. In the craniofacial reconstructive surgery the most important information the surgeon needs is in fact the bone structure and geometry. In our case the normal facial bone geometry has been disturbed and our goal is to reconstruct the normal face bone anatomy and to re-adjust the malformed position of the right zygomatic bone.

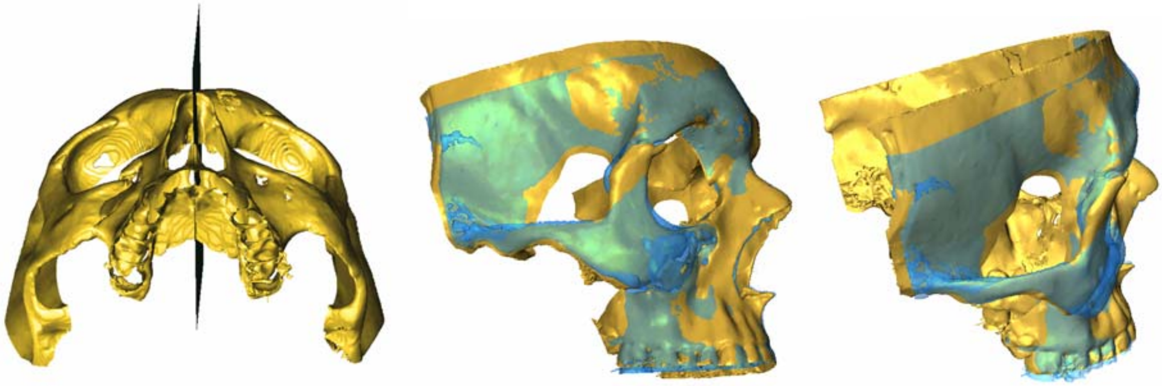

Fig. 1. The case: 24-year-old man with gun shot injury of the right zygomatic bone. The yellow surface is the original skull and the blue semi-transparent one is the mirrored healthy side aligned to the lesion side.

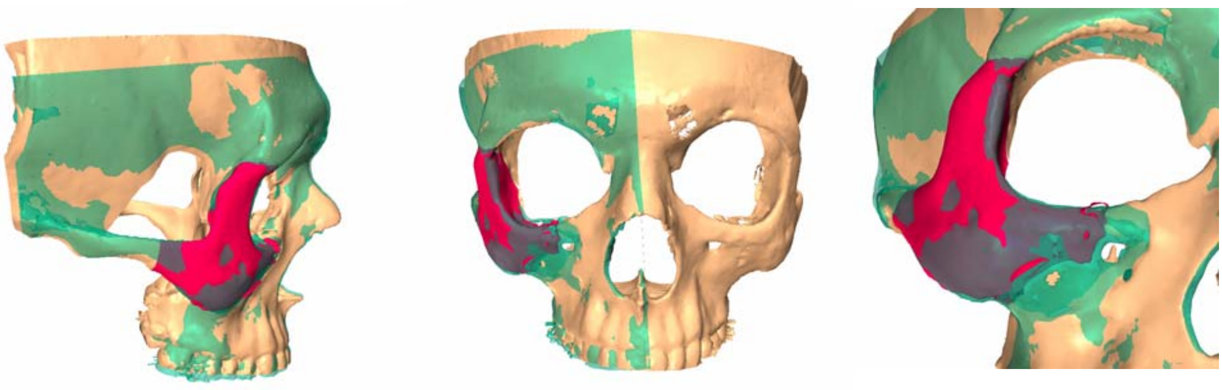

Fig. 2. The goal of the surgery planning is to reposition the malformed bone and to fix it to restore the face symmetry. The green semi-transparent surface of the mirrored healthy side superposed on the patient' skull surface defines the optimal position of the zygomatic bone. The red object is the original zygomatic bone resected and repositioned by a semi-automatic registration approach to satisfy the face symmetry optimality criteria.

To define the anatomically correct positioning of the malformed zygomatic bone we mirror the healthy site of the cranium (see Figure 1). Aligning of the mirrored healthy side of the face with the bone structures surrounding our region of interest (i.e. the zygomatic bone) let us define the correct positioning of the zygomatic bone. In Figure 2 we can observe the registration result of the mirrored healthy zygomatic bone with the malformed one. The red zygomatic bone is our correctly repositioned bone of interest. It reconstructs its correct position according to the face symmetry and defines our goal position for the intra-operative navigation stage. This method let us estimate the mathematical transformation in the dataset local coordinate system transforming the original zygomatic bone into the required anatomical position. At the next stage the surgeon will try to apply this transformation manually.

3. INTRA-OPERATIVE TRACKING AND NAVIGATION

The next step of the surgical treatment aided by the navigation system is using the generated at the previous stage virtual anatomical patient model as well as the estimated new optimal position of the zygomatic bone to facilitate the repositioning of the real patient bone to the optimal position in the real operation theatre. In Figure 3 has been shown the technical set-up allowing the realization of our new treatment approach. The components of this tracking and navigation system include the standard navigation hardware (Polaris, Northern Digital Inc. [4]) like the system control unit, position sensor, and different dynamic reference bases (DRB) (see Figure 3). The novel component of the system set-up is the navigation software using the generated at the previous stage virtual anatomical patient model and the above described technical components to navigate through the virtual and real world during the treatment. The navigation software has been implemented at the MEM Research Center, Institute for Surgical Technology and Biomechanics, University of Bern.

In the repositioning of the zygomatic bone we have to work with two anatomical objects: the patient skull and the zygomatic bone. The markers attached to the anatomical objects or instruments are tracked by at least two CCD cameras of the position sensor (see Figure 3), which calculate the markers' positions on the operative field.

Fig. 3. The navigation system set-up used in the described surgical treatment.

All immobile dynamic reference bases are firmly fixed to the patient. The DRB for the patient skull is attached to the table with the Mayfield frame fixation (see Figure 4 right) and the DRB for the zygomatic bone is attached to the zygomatic bone with the Kirschner wires. They are placed percutaneously (through the skin), thus avoiding unnecessary more invasive peering into the facial region in some cases. In addition the markers affixed to some instruments enable measuring its positions and orientations.

Fig. 4. Dynamic reference base (DRB) attached to the immobilized patient head (through the Mayfield frame) *(left)* and to his zygomatic bone by Kirschner wires accordingly (red marker tool on the right).

Fig. 5. Registration of the preoperative data with the patient by using anatomical landmarks and ICP approach [1].

The alignment of the virtual representation of the patient skull (the preoperatively generated virtual model) with the real patient in the operation room consists of two registration steps. The first one performs merging of two objects (the real and the virtual one) by using several well-defined anatomical landmarks in the skull area, which are easy to point at (with a navigated instrument). In Figure 5 the assigning of the corresponding anatomical landmarks on the patient (see Fig. 5 left) and in the virtual patient model (see in Fig. 5 right on the laptop screen) has been shown. The first registration is estimated by the least-square minimization method for several pairs of points only. This step let us align both objects in a very coarse way. The second step uses more sophisticated registration approach, namely the iterative closest point (ICP) method [1]. By scanning the surface of the real patient with a navigated instrument we can generate more points to be registered with the virtual patient surface, so the quality of registration is significantly increasing. After this double registration step we obtain a high-quality alignment between the preoperative virtual patient model and the real patient in the operation room.]

The next crucial stage is dealing with the repositioning of the real zygomatic bone towards the planned anatomically correct position. After freeing the zygomatic bone (together with the DRB rigidly fixed on it) the surgeon can reposition the real bone as well as the corresponding virtual object in the virtual model/space. The virtual model includes also the optimal position for the zygomatic bone generated at the preoperative planning stage (see Figure 6). Thus, the surgeon can quite straightforward navigate the zygomatic bone to the anatomically correct position.

The last intra-operative step exploiting the advantages of the navigation system is the inspection of the fixed at the planned position zygomatic bone by using the tracked pointer tool (see Figure 7). This last navigation step during the surgical treatment let us check the accuracy of the zygomatic bone position according to the preoperative planning. If the repositioning accuracy is not achieved, there is still the possibility to correct the bone position.

Fig. 6. Optically tracked zygomatic bone position according to the preoperative plan.

Fig. 7. Assessment of the reconstruction quality by sampling the repositioned zygomatic bone with the wireless pointer tool.

4. RESULTS

After the surgery the patient is undergoing a computed tomography acquisition. The acquired datasets enable an evaluation of the performed procedure. As we can see in Figure 8 the postoperative CT data shows high-quality reconstruction of the zygomatic bone by exploiting the navigation approach. In the bottom row of Figure 8 left we can observe the superposition of the preoperative skull surface (yellow) with the postoperative one (semi-transparent red). The blue zygomatic bone surface delineates its original position before the surgery (which had to be corrected). The semi-transparent red surface in the blue region shows the new position and orientation of the zygomatic bone (compare with the planned position in Fig. 2). The planned restoration of the face symmetry has been achieved.

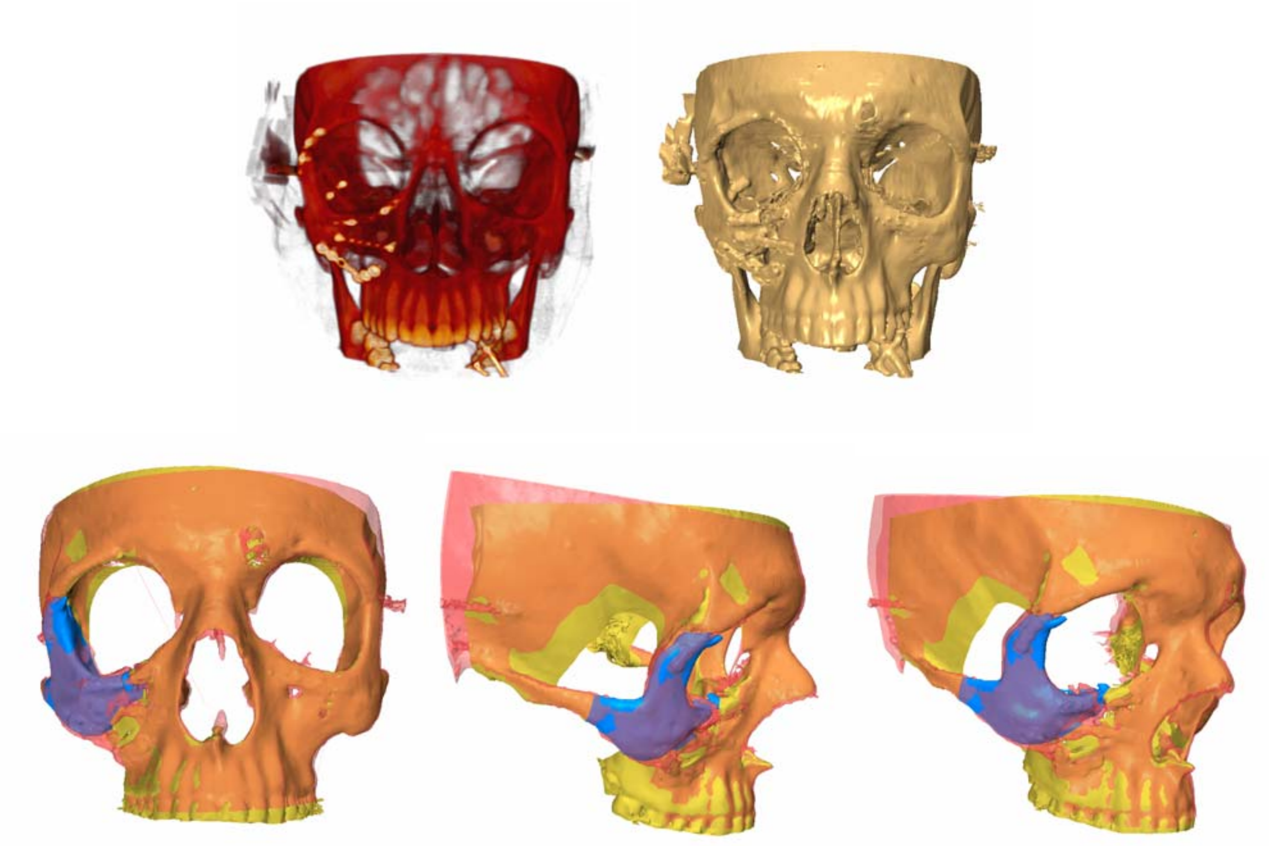

Fig. 8. The postoperative CT data shows the exact reconstruction of the zygomatic bone by using the navigation approach. Left: volume rendered CT dataset; bone plates used for fixation are visible on the left side as white spots. Right: surface rendering of the CT data shows the exact reconstruction of the face symmetry. Bottom: The superposition of the preoperative skull surface (yellow) with the postoperative one (semi-transparent red), the blue zygomatic bone surface delineates its original position before the surgery (to be corrected). The semi-transparent red surface in the blue region shows the new position and orientation of the zygomatic bone (compare with the planned position in Fig. 2).

The presented special case of the craniofacial surgery supported by the computer aided preoperative planning and the navigation system belongs to several other navigation-aided surgeries, which have been performed in the last time at the University Hospital in Basel. Besides the repositioning of the zygomatic bone, the majority of the navigation based surgical treatment regarded the osteotomy and positioning of the temporomandibular joints as well as the orbit reconstruction.

5. CONCLUSIONS

The repositioning of the zygomatic bone supported by the navigation system has been fully successful in achieving its objectives. The quality of the preoperative planning stage has a crucial influence on the quality of the navigation and tracking outcome. The better quality of the virtual patient model, the better the accuracy of intra-operative tracking and navigation procedures. A very important point is the constant assurance of the dynamic reference base rigidity. The lost of the DRB fixation rigidity leads to decreasing the tool performance accuracy. The preliminary treatment results let observe an increase in treatment quality assurance. Further navigation-aided surgical treatments are planned.

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